

Water resources systems are characterized by multiple interdependent components that produce multiple economic, environmental, ecological, and social impacts. Planners and managers working to improve the performance of these complex systems must identify and evaluate alternative designs and operating policies, comparing their predicted performance with desired goals or objectives. These alternatives are defined by the values of numerous design, management, and operating policy variables. Constrained optimization together with simulation modeling is the primary way we have of identifying the values of the unknown decision variables that will best achieve specified goals and objectives. This chapter introduces optimization and simulation modeling approaches and describes what is involved in developing and applying them to define and evaluate alternative designs and operating policies.

---

### 3.1 Introduction

There are typically many different options available to those planning and managing water resource systems. It is not always clear what set of particular design, management, and operating policy decisions will result in the best overall system performance. That is precisely why modeling is done, to estimate the performance

associated with any set of decisions and assumptions, and to predict just how well various economic, environmental, ecosystem, and social or political objectives or goals will be met.

One important criterion for plan identification and evaluation is the economic benefit or cost a plan would entail were it to be implemented. Other criteria can include the extent to which any plan meets environmental, ecological, and social targets. Once planning or management performance measures (objectives) and various general alternatives for achieving desired levels of these performance measures have been identified, models can be developed and used to help identify specific alternative plans that best achieve those objectives.

Some system performance objectives may be in conflict, and in such cases models can help identify the efficient tradeoffs among these conflicting measures of system performance. These tradeoffs indicate what combinations of performance measure values can be obtained from various system design and operating policy variable values. If the objectives are the right ones (that is, they are what the stakeholders really care about), such quantitative tradeoff information should be of value during the debate over what decisions to make (Hipel et al. 2015).

Regional water resources development plans designed to achieve various objectives typically involve investments in land and infrastructure.

Achieving the desired economic, environmental, ecological, and social objective values over time and space may require investments in storage facilities, pipes, canals, wells, pumps, treatment plants, levees, and hydroelectric generating facilities, or in fact the removal of some of them.

Many capital investments can result in irreversible economic and ecological impacts. Once the forest in a valley is cleared and replaced by a lake behind a dam, it is almost impossible to restore the site to its original condition. In parts of the world where river basin or coastal restoration activities require the removal of engineering structures, such as in the Florida Everglades discussed in Chap. 1, engineers are learning just how difficult and expensive that effort can be.

The use of planning models is not going to eliminate the possibility of making mistakes. These models can, however, inform. They can provide estimates of the different impacts associated with, say, a natural unregulated river system and a regulated river system. The former can support a healthier ecosystem that provides a host of flood protection and water quality enhancement services. The latter can provide more reliable and cheaper water supplies for off-stream users and increased hydropower and some protection from at least small floods for those living on flood-prone lands. In short, models can help stakeholders assess the future consequences, the benefits and costs, and a multitude of other impacts associated with alternative plans or management policies.

This chapter introduces some mathematical modeling approaches commonly used to study and analyze water resources systems. The modeling approaches are illustrated by their application to some relatively simple water resources planning and management problems. The purpose here is to introduce and compare some commonly used modeling methods. This is not a text on the state of the art of modeling. More realistic and more complex problems usually require much bigger and more complex models than those introduced in this book, but these bigger and more complex models are often based on the principles and techniques presented here.

The emphasis here is on the art of model development: just how one goes about constructing a model that will provide information needed to study and address particular problems, and various ways models might be solved. It is unlikely anyone will ever use any of the specific models developed in this or other chapters, simply because they will not be solving the specific example problems used to illustrate the different approaches to model development and solution. However, it is quite likely that water resources managers and planners will use the modeling approaches and solution methods presented in this book to develop the models needed to analyze their own particular problems.

The water resource planning and management problems and issues used here, or any others that could have been used to illustrate model development, can be the core of more complex models addressing more complex problems in practice. Water resources planning and management today is dominated by the use of optimization and simulation models. While computer software is becoming increasingly available for solving various types of optimization and simulation models, no software currently exists that will build those models themselves. What to include and what not to include and what parameter values to assume in models of water resource systems requires judgment, experience, and knowledge of the particular problem(s) being addressed, the system being modeled and the decision-making environment. Understanding the contents of, and performing the exercises pertaining to, this chapter will be a first step toward gaining some judgment and experience in model development and solution.

### 3.1.1 Model Components

Mathematical models typically contain one or more algebraic equations or inequalities. These expressions include variables whose values are assumed to be known and others that are unknown and to be determined. Variables that are assigned known values are usually called *parameters*. Variables having unknown values

that are to be determined by solving the model are called *decision variables*. Models are developed for the primary purpose of identifying the best values of the latter and for determining how sensitive those derived values are to the assumed parameter values.

Decision variables can include design and operating policy variables of various water resources system components. Design variables can include the active and flood storage capacities of reservoirs, the power generating capacity of hydropower plants, the pumping capacity of pumping stations, the waste removal efficiencies of wastewater treatment plants, the dimensions or flow capacities of canals and pipes, the heights of levees, the hectares of an irrigation area, the targets for water supply allocations, and so on. Operating variables can include releases of water from reservoirs or the allocations of water to various users over space and time. Unknown decision variables can also include measures of system performance, such as net economic benefits, concentrations of pollutants at specific sites and times, ecological habitat suitability values or deviations from particular ecological, economic, or hydrological targets.

Models describe, in mathematical terms, the system being analyzed and the conditions that the system has to satisfy. These conditions are often called constraints. Consider, for example, a reservoir serving various water supply users downstream. The conditions included in a model of this reservoir would include the assumption that water will flow in the direction of lower heads (that is, downstream unless it is pumped upstream), and the volume of water stored in a reservoir cannot exceed its storage capacity. Both the storage volume over time and the reservoir capacity might be unknown and are to be determined. If the capacity is known or assumed, then it is among the known model parameters.

Model parameter values, while assumed to be known, can often be uncertain. The relationships among various decision variables and assumed known model parameters (i.e., the model itself) may be uncertain. In these cases, the models can be solved for a variety of assumed conditions and parameter values. This provides an estimate of

just how important uncertain parameter values or uncertain model structures are with respect to the output of the model. This is called *sensitivity analysis*. Sensitivity analyses will be discussed in Chap. 8 in much more detail.

Solving a model means finding values of its unknown decision variables. The values of these decision variables can define a plan or policy. They can also determine the costs and benefits or the values of other measures of system performance associated with that particular management plan or policy. While the components of optimization and simulation models can include system performance indicators, model parameters and constraints, the process of model development and use also includes people. The drawing shown in Fig. 3.1 (and in Chap. 2 as well) illustrates some interested stakeholders busy studying their river basin, in this case perhaps with the use of a physical simulation model. (Further discussion of stakeholder involvement in the planning and management process is in Chap. 13).

Whether a mathematical model or physical model is being used, one important consideration is that if the modeling exercise is to be of any value, it must provide the information desired and in a form that the interested stakeholders and decision-makers can understand.

---

## 3.2 Plan Formulation and Selection

Plan formulation can be thought of as assigning particular values to each of the relevant decision variables. Plan selection is the process of evaluating alternative plans and choosing the one that best satisfies a particular objective or set of objectives. The processes of plan formulation and selection involve modeling and communication among all interested stakeholders, as the picture in Fig. 3.1 suggests.

The planning and management issues being discussed by the stakeholders in the basin pictured in Fig. 3.1 could well include surface and ground water allocations, reservoir operation, water quality management, and infrastructure capacity expansion over time.



**Fig. 3.1** These stakeholders have an interest in how their watershed or river basin is managed. Here they are using a physical model to help them visualize and address

planning and management issues. Mathematical models often replace physical models, especially for planning and management studies

### 3.2.1 Plan Formulation

Model building for defining alternative plans or policies involves a number of steps. The first is to clearly specify the issue or problem or decision (s) to be made. What are the fundamental objectives and possible alternatives? Such alternatives might require defining allocations of water to various water users, the level of wastewater treatment needed to maintain a desired water quality in a receiving stream, the capacities, and operating rules of multipurpose reservoirs and hydropower plants, and the extent and reliability of floodplain protection derived from levees. Each of these decisions may affect system performance criteria or objectives. Often these objectives include economic measures of

performance, such as costs and benefits. They may also include environmental and social measures not expressed in monetary units. (More detail on performance criteria is contained in Chap. 9).

To illustrate this plan formulation process, consider the task of designing a tank that can store a fixed volume, say  $V$ , of water. Once the desired shape has been determined, the task is to build a model that can determine the values of all the design variables and the resulting cost. Different designs result in different sizes and amounts of materials, and hence different costs. Assume the purpose of the model is to define the set of design variable values that results in the minimum total cost, for a range of values of the required volume,  $V$ .



The model of this problem must somehow relate the unknown design variable values to the cost of the tank. Assume, for example, a rectangular tank shape. The unknown design variables are the tank length,  $L$ , width,  $W$ , and height,  $H$ . These are the unknown decision variables. The objective is to find the combination of  $L$ ,  $W$ , and  $H$  values that minimizes the total cost of providing a tank capacity of at least  $V$  units of water. This volume  $V$  will be one of the model parameters. Its value is assumed known even though in fact it may be unknown and dependent in part on its cost. But for now assume  $V$  is known.

The cost of the tank will be the sum of the costs of the base, the sides, and the top. These costs will depend on the area of the base, sides, and top. Assume that we know the average costs per unit area of the base, sides, and top of the tank. These average unit costs of the base, sides, and top will probably differ. They can be denoted as  $C_{\text{base}}$ ,  $C_{\text{side}}$ , and  $C_{\text{top}}$ , respectively. These unit costs together with the tank's volume,  $V$ , are the parameters of the model. If  $L$ ,  $W$ , and  $H$  are measured in meters, then the areas will be expressed in units of square meters and the volume will be expressed in units of cubic meters. The average unit costs will be expressed in monetary units per square meter.

The final step of model building is to specify all the relations among the model parameters and decision variables. This includes defining the objective (cost) function (in this case just one unknown variable, *Cost*) and all the conditions that must be satisfied while achieving that objective. It is often helpful to first state these relationships in words. The result is a word model. Once that is written, mathematical notation can be defined and used to convert the word model to a mathematical model.

The word model for this tank design problem is to minimize total cost where:

- Total cost equals the sum of the costs of the base, the sides, and the top.
- Cost of the sides is the cost-per-unit area of the sides times the total side area.

- The total side area is twice the products of length times height and width times height.
- Cost of the base is the cost-per-unit area of the base times the total base area.
- Cost of the top is the cost-per-unit area of the top times the total top area.
- The top and base area is the product of length times width.
- The volume of the tank must at least equal the required volume capacity.
- The volume of the tank is the product of the length, width, and height of the tank.

Converting each of the above conditions to mathematical expressions using the notation defined above and inventing new notation when needed results in:

- Total cost equals the sum of the costs of the base, the sides, and the top.  
 $\text{Cost} = \text{sidecost} + \text{basecost} + \text{topcost}$
- Cost of the sides is the cost-per-unit area of the sides times the total side area.  
 $\text{sidecost} = C_{\text{side}} (\text{sidearea})$
- The total side area is twice the products of length times height and width times height.  
 $\text{sidearea} = 2(LH + WH)$
- Cost of the base is the cost-per-unit area of the base times the total base area.  
 $\text{basecost} = C_{\text{base}} (\text{basearea})$
- Cost of the top is the cost-per-unit area of the top times the total top area.  
 $\text{topcost} = C_{\text{top}} (\text{toparea})$
- The top and base area is the product of length times width.  
 $\text{toparea} = \text{basearea} = LW$
- The volume of the tank must at least equal the required volume capacity.  
 $\text{tankvolume} \geq V$
- The volume of the tank is the product of the length, width, and height of the tank.  
 $\text{tankvolume} = LWH$

Combining some of the above conditions, a mathematical optimization model can be written as:

$$\text{Minimize } Cost \quad (3.1)$$

Subject to:

$$Cost = (C_{\text{base}} + C_{\text{top}})(LW) + 2(C_{\text{side}})(LH + WH) \quad (3.2)$$

$$LWH \geq V \quad (3.3)$$

Equation 3.3 permits the tank's volume to be larger than that required. While this is allowed, it will cost more if the tank's capacity is larger than  $V$ , and hence the least-cost solution of this model will surely show that the product  $LWH$  will equal the required volume  $V$ . In practice, however, there may be practical, legal, and/or safety reasons why the decisions with respect to  $L$ ,  $W$ , and  $H$  may result in a capacity that exceeds  $V$ .

In this model, the unknown decision variables include  $Cost$ ,  $L$ ,  $W$ , and  $H$

The least-cost solution (using methods discussed in the next chapter) is

$$W = L = [2C_{\text{side}} V / (C_{\text{base}} + C_{\text{top}})]^{1/3} \quad (3.4)$$

and

$$H = V / [2C_{\text{side}} V / (C_{\text{base}} + C_{\text{top}})]^{2/3} \quad (3.5)$$

or

$$H = V^{1/3} [(C_{\text{base}} + C_{\text{top}}) / 2C_{\text{side}}]^{2/3} \quad (3.6)$$

The modeling exercise should not end here. If there is any doubt about the value of any of the parameters, a sensitivity analyses can be performed on those uncertain parameters or assumptions. In general, these assumptions could include the values of the cost parameters (e.g., the costs-per-unit area) as well as the relationships expressed in the model (that is, the model itself). How much does the total cost change with respect to a change in any of the cost parameters or with the required volume  $V$ ? How much does any decision variable change with respect to changes in those parameter values? What is the percent change in a decision variable value given

a unit percent change in some parameter value (what economists call *elasticity*)?

If indeed the decision variable values do not change significantly with respect to a change in an uncertain parameter value, there is no need to devote more effort to reducing that uncertainty. Any time and money available for further study should be directed toward those parameters or assumptions that substantially influence the model's decision variable values.

This capability of models to help identify what data or assumptions are important and what are not can guide monitoring and data collection efforts. This is a beneficial attribute of modeling often overlooked.

Continuing with the tank example, after determining, or estimating, all the values of the model parameters and then solving the model to obtain the cost-effective values of  $L$ ,  $W$  and  $H$ , we now have a design. It is just one of a number of designs that could be proposed. Another design might be for a cylindrical tank having a radius and height as well as cost decision variables. For the same volume  $V$  and unit area costs, we would find that the total cost is less, simply because the areas of the base, side, and top are less.

In the above discussion, the required volume capacity,  $V$ , has been assumed to be known. In reality, it too may be a decision variable, and what would be of greater value to decision-makers is knowing the relationship between various assumed values of  $V$  and their respective minimum costs. Such a cost function can be defined by solving the model (defined by Eqs. 3.1, 3.2 and 3.3) for various values of  $V$ .

Whatever the final outcome of our modeling efforts, there might be other considerations or criteria that are not expressed or included in the model that might be important to those responsible for plan (tank design) selection.

### 3.2.2 Plan Selection

There are various approaches to finding the "best" plan or best set of decision variable values that satisfy an objective or goal. By trial and

error, one could identify alternative plans, evaluate the performance of each plan, and select the particular plan whose performance is judged better than the others. This process could include a systematic simulation of a range of possible solutions in a search for the best. When there are a large number of feasible alternatives—that is, many decision variables and many possible values for each of them—it may no longer be practical to identify and simulate all feasible combinations of decision variable values, or even a small percentage of them. It would simply take too long. In this case it is often convenient to use an optimization procedure.

Equations 3.1–3.3 represent an optimization problem. There are an infinite number of feasible tank designs, i.e., alternative values of  $L$ ,  $W$ , and  $H$  that satisfy the volume requirement. Our job is to find the least-cost one. We can do this using a mathematical optimization method. Mathematical optimization methods are designed to make this search for the best solution (or better solutions) more efficient. Optimization methods are used to identify those values of the decision variables that satisfy specified objectives and constraints without requiring complete enumeration.

While optimization models might help identify the decision variable values that will produce the best plan directly, they are based on all the assumptions incorporated in the model. Often these assumptions are limiting. In these cases, the solutions resulting from optimization models should be analyzed in more detail, perhaps through simulation methods, to improve the values of the decision variables and to provide more accurate estimates of the impacts associated with those decision variable values. In these situations, optimization models are used for screening out the clearly inferior solutions, not for finding the very best one. Just how screening can be performed using optimization models will be discussed in the next chapter.

The values that the decision variables may assume are rarely unrestricted. Usually various functional relationships among these variables must be satisfied. This is what is expressed in constraint Eq. 3.3. For example, the tank has to

be able to contain a given amount of water. In a water allocation problem, any water allocated to and completely consumed by one user cannot simultaneously or subsequently be allocated to another user. Storage reservoirs cannot store more water than their maximum storage capacities. Technological restrictions may limit the capacities and sizes of pipes, generators, and pumps to those commercially available. Water quality concentrations should not exceed those specified by water quality standards or regulations. There may be limited funds available to spend on water resources development or infrastructure projects. These are a few examples of physical, legal, and financial conditions or constraints that may restrict the ranges of decision variable values in the solution of a model.

Equations or inequalities can generally express any physical, economic, legal, or social restrictions on the values of the decision variables. Constraints can also simply define relationships among decision variables. For example, Eq. 3.2 above defines a new decision variable called *Cost* as a function of other decision variables and model parameters. In general, constraints describe in mathematical terms the system being analyzed. They define the system components and their interrelationships, and the permissible ranges of values of the decision variables, either directly or indirectly.

Typically, there exist many more decision variables than constraints, and hence, if any feasible solution exists, there may be many such solutions that satisfy all the constraints. The existence of many feasible alternatives is a characteristic of most water resources systems planning problems. Indeed it is a characteristic of most engineering design and operation problems. The particular feasible solution or plan that satisfies the objective function—that is, that maximizes or minimizes it—is called *optimal*. It is the optimal solution of the mathematical model, but it may not necessarily be considered optimal by any decision-maker. What is optimal with respect to a model may not be optimal with respect to those involved in a planning or decision-making process. To repeat what was written in Chap. 2, models are used to provide information (useful

information, one hopes), to the decision-making process. Model solutions are not replacements for judgments of individuals involved in the decision-making process.

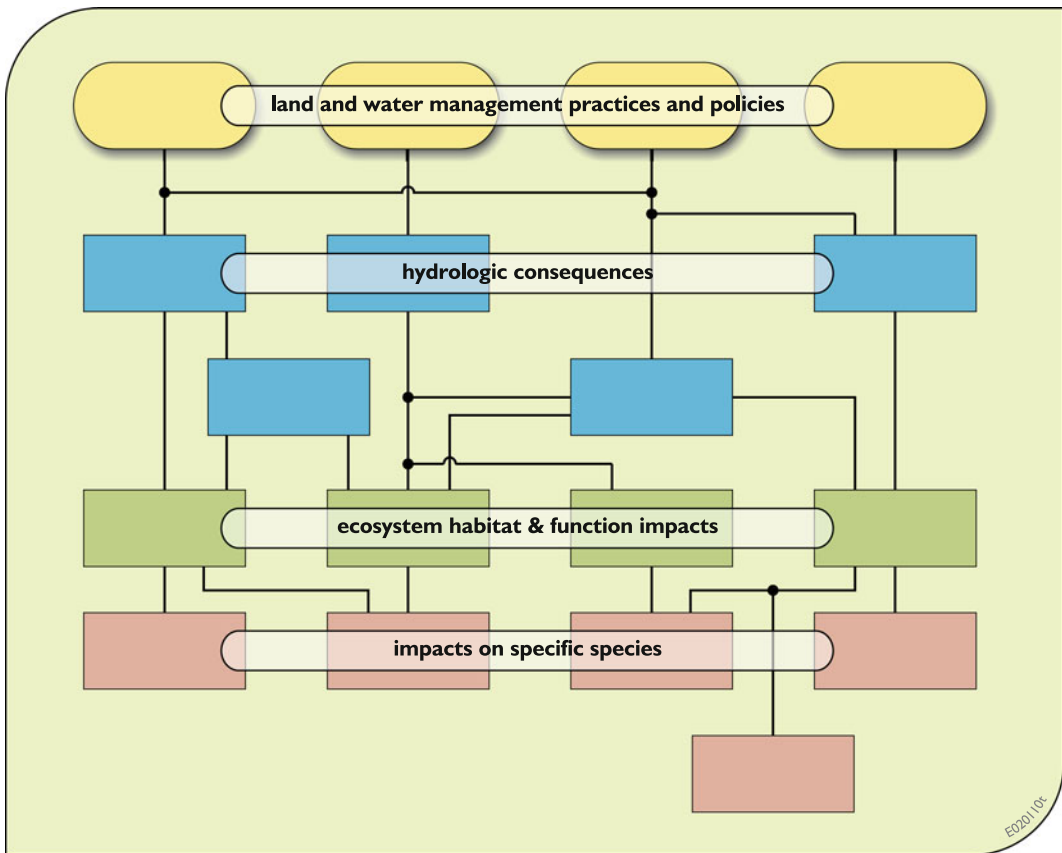
### 3.3 Conceptual Model Development

Prior to the selection or development of a quantitative model, it is often useful to develop a conceptual one. Conceptual models are non-quantitative representations of a system. The system components and their interactions are defined often by diagrams similar to Fig. 3.2.

Figure 3.2 illustrates the form of a conceptual model. This example conceptual model defines

the relationships between what land and water managers can do and the eventual ecological impacts of those actions. Once a conceptual model has been quantified (expressed in mathematical terms), it becomes a mathematical model. The model's equations typically include variables whose values are unknown and can vary, and parameters whose values are assumed known.

The values of the model's parameters need to be determined. Model calibration involves finding the best values for these parameters. Calibration is based on comparisons of the model results with observed data. Optimization methods can sometimes be used to identify the values of model parameters. This is called model calibration or identification. (Illustrations of the use of



**Fig. 3.2** An outline of a conceptual model without its detail (i.e., what exactly each component or box represents), showing the links representing interactions among

components and between management decisions and specific system impacts



optimization for estimating model parameter values are presented in the following chapter.) Sensitivity analysis may serve to identify the impacts of uncertain parameter values and show which parameter values substantially influence the model's results or solutions. Following calibration, the remaining uncertainties in the model predictions may be quantified in an uncertainty analysis as discussed in Chap. 8.

In addition to being calibrated, simulation models should also be validated or verified. In the validation or verification process, the model results are compared with an independent set of measured observations that were not used in calibration. This comparison is made to determine whether or not the model describes the system behavior sufficiently accurately.

### 3.4 Simulation and Optimization

The modeling approach to tank design discussed in the previous section focused on the use of optimization methods to identify the preferred design variable values. Similar optimization methods can be used to identify preferred design variable values and operating policies for urban stormwater runoff control or multiple reservoir systems, given various assumptions regarding parameter values and design and operating objectives. Once these preferred designs and operating policies have been identified, unless there is reason to believe that a particular alternative is really the best and needs no further analysis, each of these preferred alternatives can be further evaluated with the aid of more detailed and robust simulation models.

Simulation models address "*what if*" questions: What will likely happen over time at one or more specific places if a particular design and/or operating policy is implemented? Simulation models are not limited by many of the assumptions incorporated into optimization models. For example, the inputs to simulation models can include a much longer time series of hydrological, economic, and environmental data such as rainfall or streamflows, water supply demands, pollutant loadings and so on, than would likely

be included in an optimization model. The resulting outputs can better identify the variations of multiple system performance indicator values: that is, the multiple hydrological, ecological, economic, environmental, and social impacts that might be observed over time, given any particular system design and operating policy.

Simulating multiple sets of values defining the designs and operating policies of a water resources system can take a long time. Consider, for example, 30 infrastructure capacity variables whose values are to be determined. Even if only two possible values are assumed for each of the 30 variables (such as to exist at some predetermined capacity or not), the number of combinations that could be simulated amounts to  $2^{30}$  or in excess of  $10^9$ . Simulating and comparing even 1% of these billion at a minute per simulation amounts to over twenty years, continuously—24 h per day. Most simulation models of water resources systems contain many more variables, each having a larger range of feasible values, and are much more complex than this simple 30-binary-variable example. Mathematically, if not in reality, there could be an infinite combination of feasible values for each of the decision variables.

Simulation works well when there are only a relatively few alternatives to be evaluated, not when there are a large number of them. The trial and error process of simulation can be time consuming. An important role of optimization methods is to reduce the number of alternatives for simulation analyses. However, if only one method of analysis is to be used to evaluate a complex water resources system, simulation together with human judgment concerning which alternatives to simulate is often the method of choice.

Simulation can be based on either discrete events or discrete time periods. Most simulation models of water resources systems are designed to simulate a sequence of events over a number of discrete time periods. In each discrete time period, the simulation model converts all the initial conditions and inputs to outputs. The duration of each period depends in part on the particular system being simulated and the questions being addressed.

### 3.4.1 Simulating a Simple Water Resources System

Consider the case of a potential reservoir releasing water to downstream users (Fig. 3.3). A reservoir and its operating policy can increase the benefits each user receives over time by providing increased flows during periods of otherwise low flows relative to the user demands. Of interest is whether or not the increased benefits the water users obtain from an increased and more reliable downstream flow conditions will offset the costs of the reservoir.

Before this system can be simulated, one has to define the active storage capacity of the reservoir and how much water is to be released depending on the storage volume and time period. In other words, one has to define the reservoir operating policy. In addition, one must also define the allocation policy: how much of the released water to allocate to each user and to the river downstream of the users.

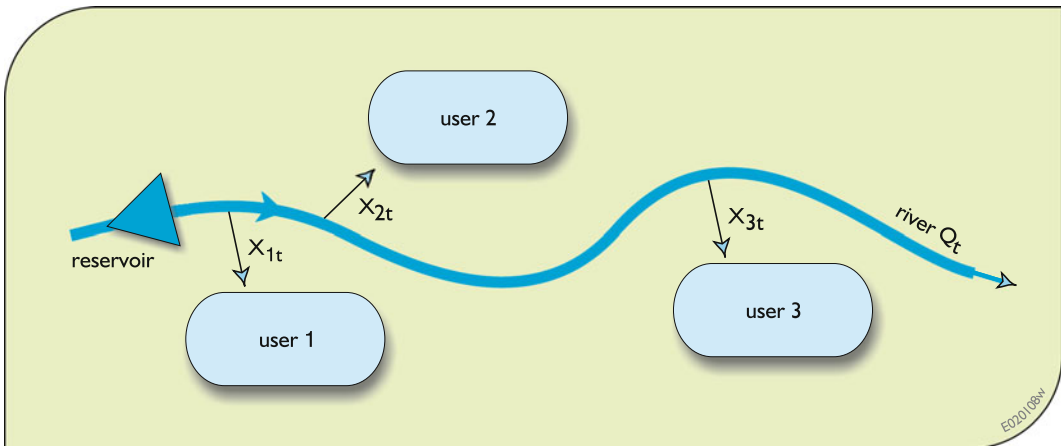
There are literally an infinite number of possible design and operating policy variable values. The next section will address the problem of screening these alternatives to find those values that are most worthy of further study using simulation.

For this simple illustration assume the operating and allocation policies are as shown in Fig. 3.4. Also for simplicity assume they apply to each discrete time period. The reservoir

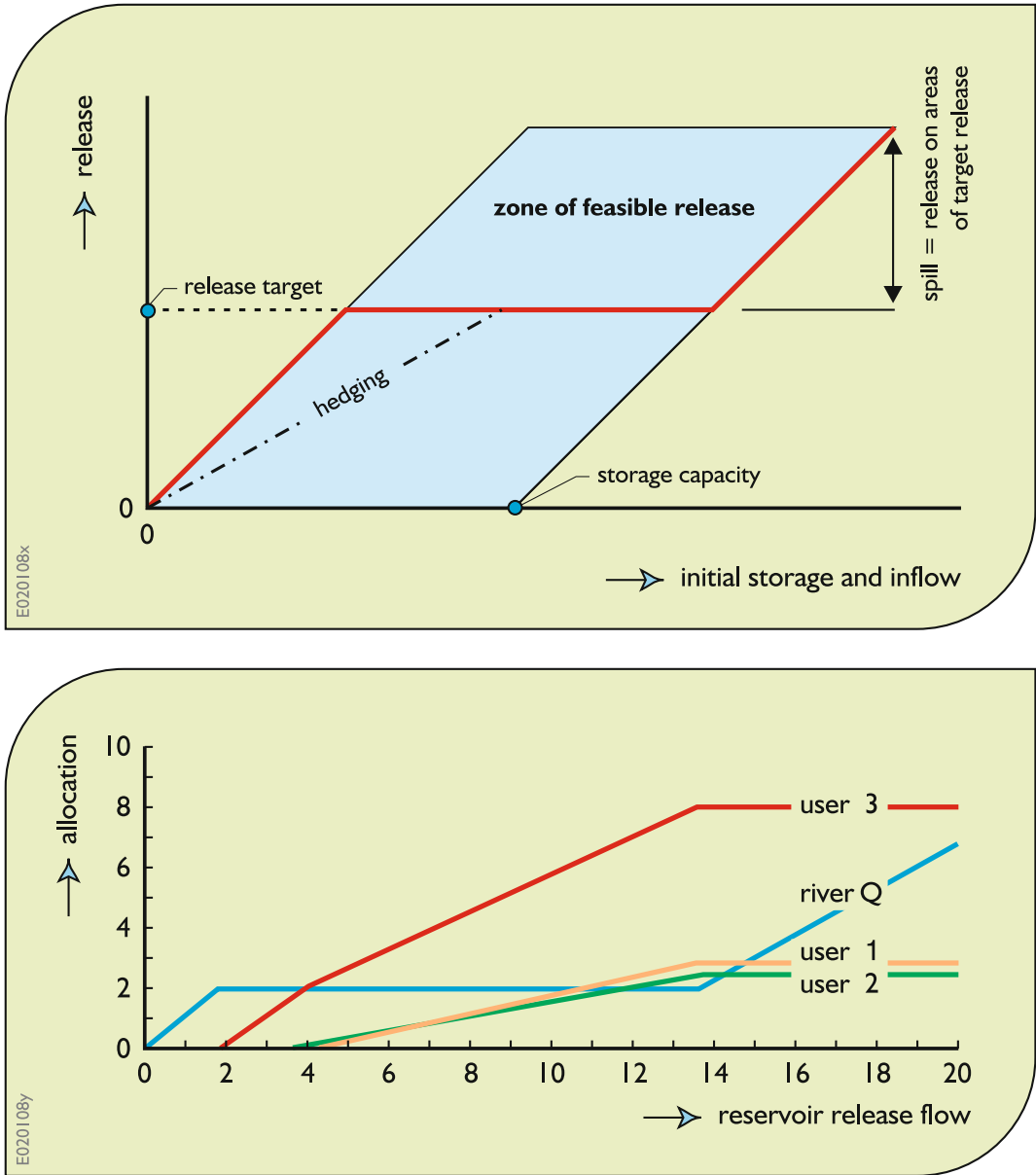
operating policy, shown as a red line in upper Fig. 3.4, attempts to meet a release target. If insufficient water is available, all the water will be released in the time period. If the inflow exceeds the target flow and the reservoir is full, a spill will occur.

This operating policy is sometimes called the “standard” operating policy. It is not usually followed in practice. Most operators, as indeed specified by most reservoir operating policies, will reduce releases in times of drought in an attempt to save some water in the reservoir for future releases in case of an extended period of low inflows. This is called a hedging policy. Any reservoir release policy, including a hedging policy, can be defined within the blue portion of the release policy plot shown in Fig. 3.4. The dash-dot line in Fig. 3.4 is one such hedging function. Once defined, any reservoir operating policy can be simulated.

The simulation process for the three-user system is shown in Fig. 3.5. It proceeds from one time period to the next. The reservoir inflow, obtained from a database, is added to the existing storage volume, and a release is determined based on the release policy (upper Fig. 3.4). Once the release is known, the final storage volume is computed and this becomes the initial volume for the next simulation time period. The reservoir release is then allocated to the three downstream users and to the river downstream of those users as defined by the allocation policy



**Fig. 3.3** Conceptual model of a reservoir water allocation system to be simulated



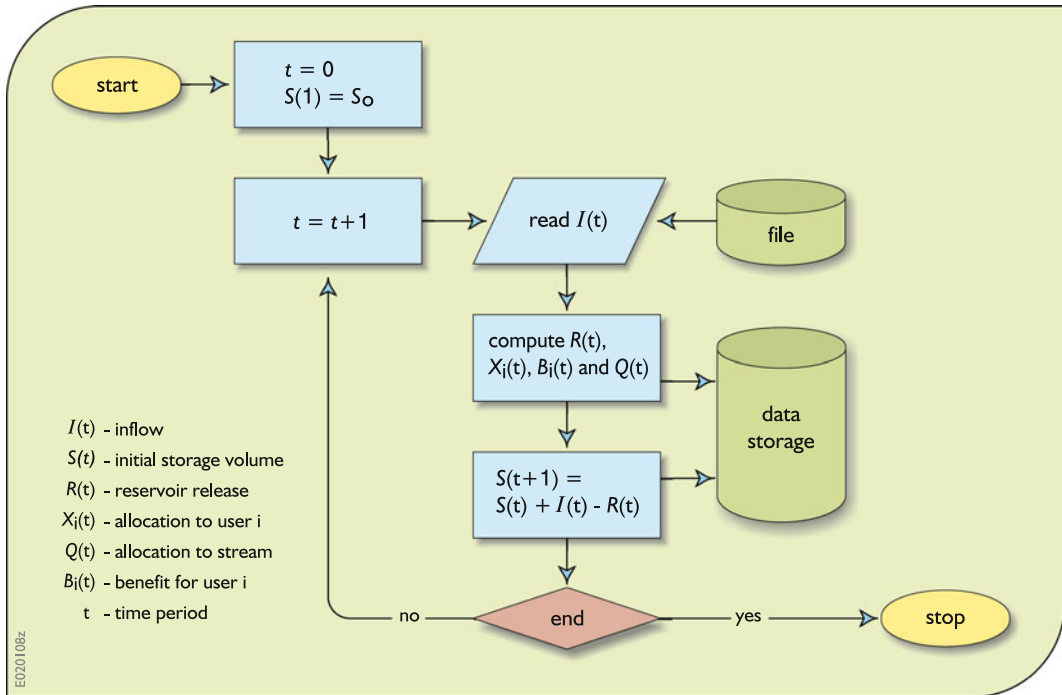
**Fig. 3.4** Reservoir operating policy defining the reservoir release to be made as a function of the current storage volume and current inflow and the allocation policy for the river flow downstream of the reservoir. The blue zone

in the reservoir release policy indicates the zone of feasible releases. It is physically impossible to make releases represented by points outside that blue zone

(lower Fig. 3.4). The resulting benefits can be calculated and stored in an output database.

Additional data including storage volumes, releases, and the allocations themselves can also be stored in the output database, as desired. The

simulation process continues for the duration of the simulation run. Then the output data can be summarized for later comparison with other simulation results based on other reservoir capacities, operation policies and/or allocation policies.



**Fig. 3.5** Flow diagram of the reservoir—user allocation system simulation process. The simulation terminates after some predefined number of simulation time steps

It would not be too difficult to write a computer program to perform this simulation. In fact, it can be done on a spreadsheet. However as easy as that might be for anyone familiar with computer programming or spreadsheets, one cannot expect it to be easy for many practicing water resources planners and managers who are not doing this type of work on a regular basis. Yet they might wish to perform a simulation of their particular system, and to do it in a way that facilitates changes in many of its assumptions. Computer programs capable of simulating a wide variety of water resources systems are becoming increasingly available. Simulation programs together with their interfaces that facilitate the input and editing of data and the display of output data are typically called decision support systems. Their input data define the components of the water resources system and their configuration. Inputs also include hydrological data and design and operating policy data. These generic simulation programs are capable of simulating surface and ground water flows, storage volumes

and qualities under a variety of system infrastructure designs and operating policies.

### 3.4.2 Defining What to Simulate

Before the simple system shown in Fig. 3.3 can be simulated the design and operating policy of the system, i.e., the information shown in Fig. 3.4 needs to be defined. One way to do this is to use optimization. Optimization is driven by an objective function. Assume an overall measure of system performance has been decided upon, and can be expressed as a function of the decision variables. These decision variables include all the information in Fig. 3.3, namely the reservoir capacity and reservoir storage and release and water user allocation decisions in each time period. Of interest are the values of these decision variables that achieve the highest level of system performance. The use of an optimization model will help in defining those variable values.

Expressed in words, the optimization model is to be developed and used to identify the decision variable values that maximize system performance. Let  $B(K, S, R, A)$  represent the overall system performance measure, as a function of the reservoir capacity  $K$ , and all the initial storage volumes,  $S(t)$ , releases,  $R(t)$ , and water allocations to users  $i$ ,  $A(i, t)$ , in each time period  $t$  for a total of  $T$  time periods. Hence the objective is to

$$\text{maximize } B(K, S, R, A) \quad (3.7)$$

while making sure that a mass balance of water is maintained in the reservoir over time.

$$S(t) + \text{Inflow}(t) - R(t) = S(t+1) \quad \text{for each period } t \\ \text{(and period } T+1 = 1) \quad (3.8)$$

These mass balance equations define the relationship between initial,  $S(t)$ , and final,  $S(t+1)$  storage volume values in each period  $t$ , and equate the final storage value in each period to the initial value in the following period. Finally, it assumes the entire simulation process repeats itself after every  $T$  years.

The next set of constraints ensure that the storage volumes,  $S(t)$ , do not exceed the reservoir storage capacity  $K$  and that the allocations,  $A(i, t)$ , to the three water users  $i$  do not exceed the reservoir release,  $R(t)$ , less the amount to remain in the stream,  $Q(t)$ .

$$S(t) \leq K \quad \text{for each period } t. \quad (3.9)$$

$$A(1, t) + A(2, t) + A(3, t) \leq R(t) - Q(t) \quad (3.10) \\ \text{for each period } t.$$

This simple example ignores many of the details one should consider when modeling reservoirs and water users, and many of these details will be discussed, and modeled, in subsequent chapters. But for now the model is sufficient to find values for each decision variable shown in upper portion of Fig. 3.4. The allocation policies shown in the lower portion of Fig. 3.4 can be obtained by solving a separate

single-period optimization model containing only the allocation benefits as the objective,  $B(A)$ , and constraint 3.10 for a single period, and various values of the water available,  $R - Q$ , assuming the benefits,  $B(A)$ , do not change over time.

$$\text{Maximize } B(A(1), A(2), A(3)) \quad (3.11)$$

Subject to:

$$A(1) + A(2) + A(3) \leq R - Q \quad (3.12) \\ \text{for various values of } R, \text{ given } Q.$$

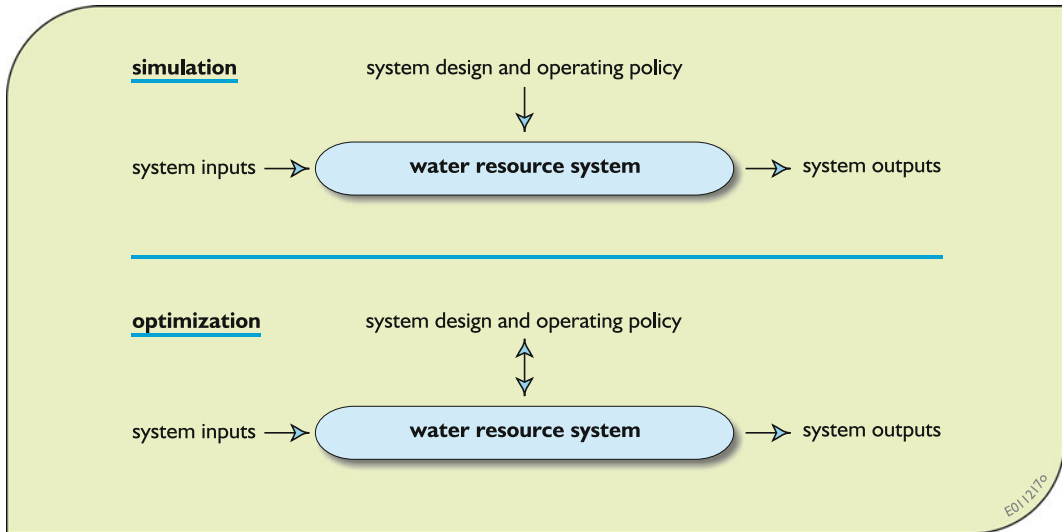
### 3.4.3 Simulation Versus Optimization

Unlike simulation models, the solutions of optimization models are based on objective functions that are to be maximized or minimized. The objective function and constraints of an optimization model contain decision variables that are unknown and parameters whose values are assumed known. Constraints are expressed as equations and inequalities. The tank model (Eqs. 3.1, 3.2 and 3.3) is an example of an optimization model. So is the reservoir water allocation model, Eqs. 3.7–3.10 and the single-period allocation model Eqs. 3.11 and 3.12.

The solution of an optimization model, if one exists, contains the values of all of the unknown decision variables. It is mathematically optimal in that the values of the decision variables satisfy all the constraints and maximize or minimize an objective function. This “optimal” solution is of course based on the assumed values of the model parameters, the chosen objective function and the structure of the model itself. At best these assumptions can only approximate reality.

The assumptions made to permit model solution by optimization solution procedures (algorithms), may justify a more detailed and more realistic simulation to check and improve on any solution obtained from that optimization. While the results from a simulation model may be more realistic, both optimization and simulation models are approximations of the real system being modeled. The optimal solution of any model is optimal *only with respect to the particular model*,





**Fig. 3.6** Distinguishing between simulation and optimization modeling. Simulation addresses “what if” questions; optimization can address “what should be”

questions. Both types of models are typically used in water resources planning and management studies

not necessarily with respect to the real system. It is important to realize this limited meaning of the word “optimal,” a term commonly found in papers published by water resources and other systems analysts, planners, and engineers.

Figure 3.6 illustrates the broad differences between simulation and optimization. Optimization models need explicit expressions of objectives. Simulation models do not. Simulation simply addresses “what-if” scenarios—what may happen if a particular scenario is assumed or if a particular decision is made. Users of simulation models must specify the values of design and operating decision variables before a simulation can be performed. Once these values of all decision variables are defined, simulation can provide more precise estimates of the impacts that may result from those decisions.

While optimization will tell us what we should do—what the best decision is—that solution is often based on many limiting assumptions. Because of this, we need to use optimization not as a way to find the best solution, but to define a relatively small number of good alternatives that can later be tested, evaluated, and improved by means of more detailed simulations. This process of using optimization to reduce the large number

of plans and policies to a few that can then be simulated and better evaluated is often called *preliminary screening*.

### 3.5 Conclusions

This chapter has reviewed some basic types of models and presented guidelines for their use. Generic models for water resources system analyses are increasingly becoming available, saving many organizations from having to develop their own individual models. While many readers of this book may get involved in writing their own models, most of those involved in water resources planning and management will be using existing models and analyzing and presenting their results. The information provided in this book is intended to help those who wish to build their modeling skills. Such skills will be useful to those involved in water resource systems planning and management activities. Such skills may be useful even to those who are expected to oversee or evaluate the model results of others (say from various UN, World Bank, or national aid agencies) who are involved in analyzing particular water resource systems in particular regions of the world.

## Reference

Hipel, K. W., Fang, L., Cullmann, J., & Bristow, M. (Eds.). (2015). *Conflict resolution in water resources and environmental management*. Cham, Heidelberg, New York, Dordrecht, London: Springer.

## Additional References (Further Reading)

- Abbott, M. B. (1999). Introducing hydroinformatics. *Journal of Hydroinformatics*, 1(1), 3–20.
- Beck, M. B. (1987). Water quality modeling: A review of the analysis of uncertainty. *Water Resources Research*, 23, 1393–1442.
- Biswas, A. K. (Ed.). (1997). *Water resources: Environmental planning, management, and development*. New York: McGraw-Hill.
- Bobba, A., Ghosh, S., Vijay, P., & Bengtsson, L. (2000). Application of environmental models to different hydrological systems. *Ecological Modelling*, 125, 15–49.
- Booch, G. (1994). *Object-oriented analysis with applications*. Benjamin Cummings: Redwood City.
- Chan, H. W., & Lam, P. F. (1997). Visualizing Input and output analysis for simulation. *Simulation Practice and Theory*, 5(5), 425–453.
- Edsall, R. M., Harrower, M., & Mennis, J. L. (2000). Tools for visualizing properties of spatial and temporal periodicities in geographic data. *Computers & Geosciences*, 26(1), 109–118.
- Fedra, K., & Jamieson, D. G. (1996). An object-oriented approach to model integration: A river basin information system example. In: K. Kowar & H. P. Nachtnebel (Eds.), *Proceedings of the HydroGIS'96 Conference*, (vol. 235, pp. 669–676). Vienna: IAHS Press.
- Guariso, G., & Werthner, H. (1989). *Environmental decision support systems*. New York: Ellis Horwood-Wiley.
- Ho, J. K. K., & Sculli, D. (1997). The scientific approach to problem solving and decision support systems. *International Journal of Production Economics*, 48(3), 249–257.
- Hufschmidt, M. M., & Fiering, M. B. (1966). *Simulation in the design of water resource systems*. Cambridge, Massachusetts: Harvard University Press.
- Lam, D. C. L., Mayfield, C. I., & Sawyne, D. A. (1994). A prototype information system for watershed management and planning. *Journal of Biological Systems*, 2(4), 499–517.
- Lam, D., & Swayne, D. (2001). Issues of EIS software design: Some lessons learned in the past decade. *Environmental Modeling and Software*, 16(5), 419–425.
- LAW, A. M., & KELTON, W. D. (2000). *Simulation modeling and analysis* (3rd ed.). Boston, Mass: McGraw-Hill.
- Loucks, D. P., Stedinger, J. S., & Haith, D. A. (1981). *Water resources systems planning and analysis*. Englewood Cliffs, N.J.: Prentice Hall.
- Maass, A., Hufschmidt, M. M., Dorfman, R., Thomas, H. A., Marglin, S. A., & Fair, G. M. (1962). *Design of water resources systems*. Cambridge, UK: Harvard University Press.
- Reitsma, R. F., & Carron, J. C. (1997). Object-oriented simulation and evaluation of river basin operations. *Journal of Geographic Information and Decision Analysis*, 1(1), 9–24.
- Rizzoli, A. E., Davis, J. R., & Abel, D. J. (1998). Model and data integration and re-use in environmental decision support systems. *Decision Support Systems*, 24(2), 127–144.
- Rizzoli, A. E., & Young, W. J. (1997). Delivering environmental decision support systems: Software tools and techniques. *Environmental Modeling & Software*, 12(2–3), 237–249.
- Sargent, R. G. (1982). Verification and validation of simulation models. In F. E. Cellier (Ed.), *Progress in modelling and simulation* (pp. 159–169). London: Academic Press.
- Sargent, R. G. (1984a). A tutorial on verification and validation of simulation models. In: S. Sheppard, U. Pooch, & D. Pegden (Eds.), *Proceedings of the 1984 Winter Simulation Conference* (pp. 115–21). Piscataway: N.J. Institute of Electrical and Electronics Engineers.
- Sargent, R. G. (1984b). Simulation model validation. In: T. I. Ören, B. P. Zeigler, & M. S. Elzas (Eds.), *Simulation and model-based methodologies: An integrative view* (pp. 537–55). Berlin: Springer (No. 10 in the series: NATO ASI Series F: Computer and Systems Sciences).
- Scholten, H., Van Waveren, R. H., Groot, S., Van Geer, F. C., Wösten, J. H. M., Koeze, R. D., et al. (2000). *Good Modelling Practice in Water Management, Proceedings Hydroinformatics 2000*. Cedar Rapids, Iowa: International Association for Hydraulic Research.
- Singh, V. P. (Ed.). (1995). *Computer models of watershed hydrology*. Littleton, Colorado: Water Resources Publications.
- Sun, L., & Liu, K. (2001). A method for interactive articulation of information requirements for strategic decision support. *Information and Software Technology*, 43(4), 247–263.
- Van Waveren, R. H., Groot, S., Scholten, H., Van Geer, F. C., Wösten, J. H. M., Koeze, R. D., et al. (1999). *Good modelling practice handbook* (STOWA report 99-05). Lelystad, The Netherlands: Dutch Department of Public Works, Institute for Inland Water Management and Waste Water Treatment (report 99.036).
- Watkins, D. W. Jr., (Ed.). (2013). *Water resources systems analysis through case studies: Data and models for decision making* (168 pp). Reston, VA: ASCE Press.

Young, P. (1998). Data-based mechanistic modeling of environmental, ecological, economic and engineering systems. *Environmental Modeling & Software*, 13, 105–122.

Young, W. J., Lam, D. C. L., Ressel, V., & Wong, J. W. (2000). Development of an environmental flows decision support system. *Environmental Modeling & Software*, 15, 257–265.

Zeigler, B. P. (1976). *Theory of modelling and simulation*. Malabar, Florida: Robert E. Krieger.

Zeiler, M. (1999). *Modeling our world: The ESRI guide to geodatabase design*. Redlands, California: ESRI.

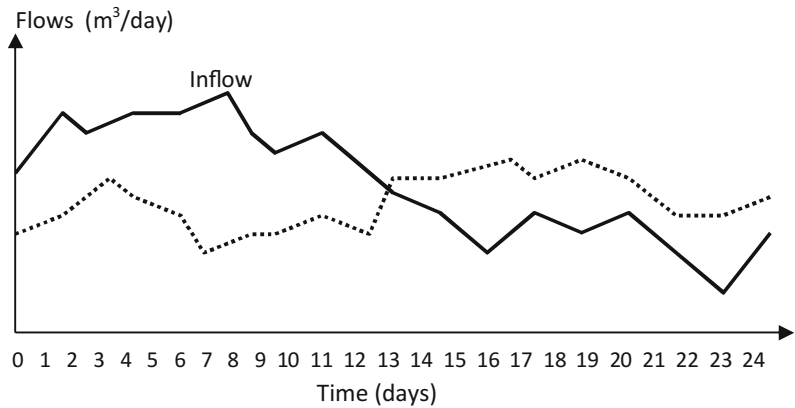
3.6 Consider the following five alternatives for the production of energy ( $10^3$  kwh/day) and irrigation supplies ( $10^6$  m<sup>3</sup>/month):

Alternative	Energy production	Irrigation supply
A	22	20
B	10	35
C	20	32
D	12	21
E	6	25

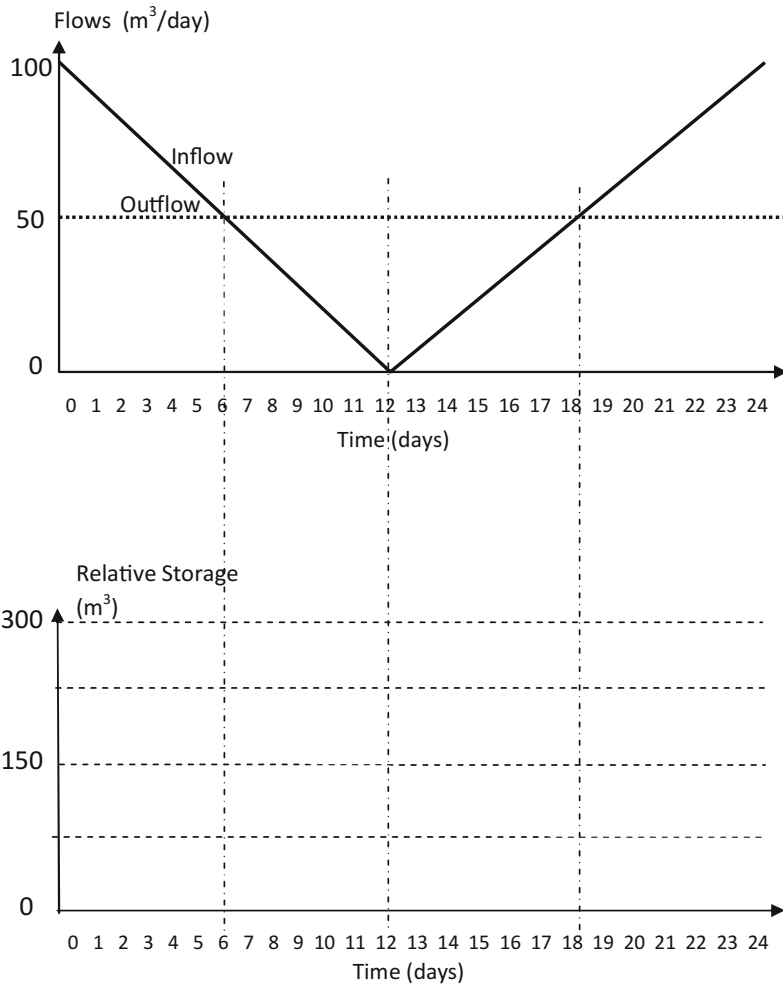
Exercises

- 3.1 Briefly outline why multiple disciplines are needed to efficiently and effectively manage water resources in major river basins, or even in local watersheds.
- 3.2 Describe in a page or two what some of the water management issues are in the region where you live.
- 3.3 Define adaptive management, shared vision modeling, and sustainability.
- 3.4 Distinguish what a manager does from what an analyst (modeler) does.
- 3.5 Identify some typical or common water resources planning or management problems that are suitable for analysis using quantitative systems analysis techniques.

- Which alternative would be the best in your opinion and why? Why might a decision-maker select alternative E even realizing other alternatives exist that can give more hydropower energy and irrigation supply?
- 3.7 Define a model similar to Eqs. 3.1–3.3 for finding the dimensions of a cylindrical tank that minimizes the total cost of storing a specified volume of water. What are the unknown decision variables? What are the model parameters? Develop an iterative approach for solving this model.
  - 3.8 Briefly distinguish between simulation and optimization.
  - 3.9 Consider a tank, a lake or reservoir or an aquifer having inflows and outflows as shown in the graph below.



- (a) When was the inflow its maximum and minimum values?
- (b) When was the outflow its minimum value?
- (c) When was the storage volume its maximum value?
- (d) When was the storage volume its minimum value?
- (e) Write a mass balance equation for the time series of storage volumes assuming constant inflows and outflows during each time period.
- 3.10 Given the changing inflows and constant outflow from a tank or reservoir, as shown in the graph below, sketch a plot of the



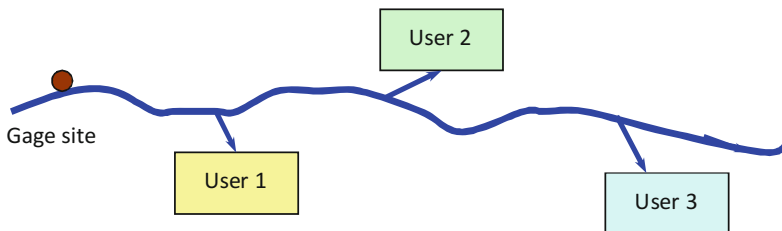
storage volumes over the same period of time, beginning at 150. Show how to determine the value of the slope of the storage volume plot at any time from the inflow and outflow ( $= 50 \text{ m}^3/\text{day}$ ) graph below.

- 3.11 Describe, using words and a flow diagram, how you might simulate the operation of a storage reservoir over time. To simulate a reservoir, what data do you need to have or know?
- 3.12 Identify and discuss a water resources planning situation that illustrates the need for a combined optimization-simulation study in order to identify the best plan and its impacts.
- 3.13 Write a flow chart/computer simulation program for computing the maximum yield of water that can be obtained given any value of active reservoir storage capacity,  $K$ , using.

Year $y$	Flow $Q_y$	Year $y$	Flow $Q_y$
1	5	9	3
2	7	10	6
3	8	11	8
4	4	12	9
5	3	13	3
6	3	14	4
7	2	15	9
8	1		

Find the values of the storage capacity  $K$  required for yields of 2, 3, 3.5, 4, 4.5, and 5.

- 3.14 How many different simulations of a water resource system would be required to ensure that there is at least a 95% chance that the best solution obtained is within the better 5% of all possible solutions that could be obtained? What assumptions must be made in order for your answer to be valid? Can any statement be made comparing the value of the best solution obtained from the all the simulations to the value of the truly optimal solution?
- 3.15 Assume in a particular river basin 20 development projects are being proposed. Assume each project has a fixed capacity and operating policy and it is only a question of which of the 20 projects would maximize the net benefits to the region. Assuming 5 min of computer time is required to simulate and evaluate each combination of projects, show that it would require 36 days of computer time even if 99% of the alternative combinations could be discarded using "good judgment." What does this suggest about the use of simulation for regional interdependent multiproject water resources planning?
- 3.16 Assume you wish to determine the allocation of water  $X_j$  to three different users  $j$ , who obtain benefits  $R_j(X_j)$ . The total water available is  $Q$ . Write a flow chart showing how you can find the allocation to each user that results in the highest total benefits.
- 3.17 Consider the allocation problem illustrated below.





The allocation priority in each simulation period  $t$  is:

First 10 units of streamflow at the gage remain in the stream.

Next 20 units go to User 3.

Next 60 units are equally shared by Users 1 and 2.

Next 10 units go to User 2.

Remainder goes downstream.

This will be a graph of the allocation as a function of the flow at the allocation site.

- (b) Simulate this allocation policy using any river basin simulation model such as RIBASIM, WEAP, Modsim, or other selected model, including your own, for any specified inflow series ranging from 0 to 130 units.

- (a) Assume no incremental flow along the stream and no return flow from users. Define the allocation policy at each site.

**Open Access** This chapter is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits any noncommercial use, duplication, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.



The images or other third party material in this chapter are included in the work's Creative Commons license, unless indicated otherwise in the credit line; if such material is not included in the work's Creative Commons license and the respective action is not permitted by statutory regulation, users will need to obtain permission from the license holder to duplicate, adapt or reproduce the material.